

To appear in the April 10, 2000 Astrophysical Journal

## DISTANCE DEPENDENCE IN THE SOLAR NEIGHBORHOOD AGE-METALLICITY RELATION

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### ABSTRACT

The age-metallicity relation for F and G dwarf stars in the solar neighborhood, based on the stellar metallicity data of Edvardsson et al. (1993), shows an apparent scatter that is larger than expected considering the uncertainties in metallicities and ages. A number of theoretical models have been put forward to explain the large scatter. However, we present evidence, based on Edvardsson et al. (1993) data, along with Hipparcos parallaxes and new age estimates, that the scatter in the age-metallicity relation depends on the distance to the stars in the sample, such that stars within 30 pc of the Sun show significantly less scatter in  $[\text{Fe}/\text{H}]$ . Stars of intermediate age from the Edvardsson et al. sample at distances 30-80 pc from the Sun are systematically more metal-poor than those more nearby. We also find that the slope of the apparent age-metallicity relation is different for stars within 30 pc than for those stars more distant. These results are most likely an artifact of selection biases in the Edvardsson et al. star sample. We conclude that the intrinsic dispersion in metallicity at fixed age is  $< 0.15$  dex for field stars in the solar neighborhood, consistent with the  $< 0.1$  dex for Galactic open star clusters and the interstellar medium.

*Subject headings:* Galaxy: abundances – Galaxy: solar neighborhood – Galaxy: evolution – stars: abundances

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## 1. Introduction

The age-metallicity relation (AMR) for stars, coupled with the stellar metallicity distribution and the star formation history, is a fundamental constraint on models for the chemical evolution of the solar neighborhood, providing the time history of the enrichment of the interstellar medium. Defining this relation, however, has not been a trivial task, as it requires obtaining the ages, distances, metallicities, and kinematics for a large sample of stars. The age-metallicity relation established by Twarog (1980) was a key constraint on chemical evolution models for the solar neighborhood. However, this study lacked kinematic information for the stars, and thus on the amount of contamination by stars not born in the solar neighborhood (such as thick disk stars, whose connection to galactic evolution is uncertain at present).

More recently, Edvardsson et al. (1993; hereafter Edv93) published abundances for numerous heavy elements in field F and G dwarf stars having kinematic information. These data have provided a wealth of information on abundances and abundance ratios as a function of time and kinematics in the galactic disk. The sample of stars chosen had a variety of photometric information and space velocities, allowing them to be placed on the HR diagram and in the appropriate kinematic population. One surprising result from this study was that the AMR derived by Edv93 showed much greater scatter (inferred to be 0.6-1.0 dex by some papers) than could be attributed to observational uncertainties. This result suggested that chemical evolution in the solar neighborhood has been highly inhomogeneous over time.

A number of theoretical explanations for the scatter in the local AMR have been proposed, including: radial diffusion of stellar orbits (François & Matteucci 1993; Wielen, Fuchs, & Dettbarn 1996); episodic infall of metal-poor gas (Edv93; Pilyugin & Edmunds 1996); and sequential or stochastic enrichment by stellar populations (van den Hoek & de Jong 1997; Copi 1997). Which mechanism might be most important is unknown, but there is no lack of explanations. On the other hand, the inference of large scatter is inconsistent with abundance measurements in nearby spiral and irregular galaxies (e.g., Kennicutt & Garnett 1996 and Kobulnicky & Skillman 1996), and in the local ISM (Meyer, Jura, & Cardelli 1998), which show that dispersions in ISM abundances are rather small on kiloparsec scales or less. It is difficult to understand how a largely homogeneous ISM could give rise to a large dispersion in stellar metallicities. The apparent dispersion in the Edv93 data is inconsistent with the smaller dispersion derived by Twarog (1980) as well.

Therefore, it seems appropriate to re-examine the AMR. Edv93 warned that their star sample was not an unbiased sample (see also Nissen 1995) and thus should be used cautiously in interpreting the AMR. We will demonstrate below that there is a systematic dependence in the amount of scatter in the AMR on the properties of the stars, in particular on stellar distance. We will conclude that the intrinsic scatter in the AMR is smaller than has sometimes been inferred.

## 2. The Stellar Sample

The Edv93 metallicity sample consisted of 189 somewhat evolved F and G stars within 80 pc of the sun. The sample was selected to have roughly equal numbers of stars in nine metallicity bins from  $[M/H] = +0.2$  to  $-0.9$ , where  $[M/H]$  is the logarithmic metallicity relative to solar. In order to obtain such sampling, Edv93 had to observe fainter and more distant stars to obtain a sufficient number of stars in the low-metallicity bins.

Of this sample, eleven stars are spectroscopic binaries, which can have larger uncertainties in distances and ages; another eleven stars had large uncertainties in their proper motions. We have excluded these from our analysis. Seven other stars had no age estimates and were also excluded. We have retained the stars labeled ‘hook’ stars by Edv93, although their ages may be systematically underestimated by up to 0.15 dex.

Not all of the stars in the Edv93 sample had trigonometric parallaxes in 1993, and so they relied on distances based on their Strömngren photometry. Since then, parallaxes from the Hipparcos catalog (ESA 1997) have become available for all of these stars. Ng & Bertelli (1998) have published revised ages for the stars based on the Hipparcos parallaxes and the more recently computed stellar evolution tracks of Bertelli et al. (1994). Comparison of the revised stellar ages with the Edv93 ages showed little systematic difference (Ng & Bertelli 1998), indicating that age uncertainties are not the main source of the scatter in age vs. metallicity. However, there is a slight reduction in the scatter when the Hipparcos distances and Ng & Bertelli (1998) ages are used; we will therefore base the following discussion on the revised ages from Tables 5 and 6 of Ng & Bertelli (1998) and Hipparcos distances.

## 3. Distance Dependence of the Scatter in Metallicity

Figure 1 shows the AMR plot for  $[Fe/H]$  based on our selected subset of the Edv93 stars. Assuming the quoted observational uncertainties of  $\pm 0.1$  dex in  $[Fe/H]$  and age, a Monte Carlo analysis indicates that an additional Gaussian dispersion in  $[Fe/H]$  of  $\pm 0.15$ - $0.2$  dex beyond the observational scatter is required to account for the observed scatter.

We were originally concerned that uncertainties in the distances to the stars could introduce errors into their ages, and thus could cause artificially large scatter in the AMR. Therefore, we examined the scatter as a function of distance to the stars. We made a simple division of the sample into two groups: a nearby group with distances less than 30 parsecs from the sun (89 stars), and a more distant set containing the remaining 71 stars with distances greater than 30 parsecs (which extends out to 80 parsecs). Figure 2 shows the age-metallicity diagrams for the two groups of stars. The comparison is remarkable: the nearest stars show an obvious reduction in scatter in  $[Fe/H]$  at a given age than the full sample of Figure 1, especially for the intermediate ages ( $\log \tau$  between 0.5 and 0.9 in Gyrs). In fact, Figure 2 reveals a striking asymmetry in the metallicity

distribution for the nearby and more distant stars. While for the nearby stars  $[\text{Fe}/\text{H}]$  rises steeply with decreasing age and then levels off for the younger stars, for the more distant stars a more gradual increase in  $[\text{Fe}/\text{H}]$  appears to be the case. To show that this difference is not a simple statistical fluctuation, we examine the stars in the range  $0.5 < \log \tau < 0.9$ , where the more distant sample shows a dearth of metal-rich stars and an enhancement in the number of metal-poor stars compared to the nearby sample. We show the distributions of  $[\text{Fe}/\text{H}]$  for the near and far stars within this age range in Figure 3. A Mann-Whitney test rejects the hypothesis that these two samples come from populations with the same mean  $[\text{Fe}/\text{H}]$  at the 99.99% confidence level, while a Kolmogorov-Smirnov test indicates that the probability that these two samples are drawn from the same population is only  $8.3 \times 10^{-4}$ . Thus, it appears that the difference between these two groups of stars is highly significant. (We see the same patterns in plots for other elements as well.) The difference suggests that the more distant sample may include stars whose chemical properties do not reflect the evolution of the disk in the solar neighborhood. This is plausible since the more distant stars sample a volume that is 18 times larger than the stars within 30 pc.

We explore the properties of the two star samples further. Figure 4 plots  $[\text{Fe}/\text{H}]$  vs. the mean stellar orbital radius  $R_{\text{mean}}$  (from Edv93), Figure 5 shows  $[\text{Fe}/\text{H}]$  vs. the maximum height  $Z_{\text{max}}$  of each star above the Galactic plane (one star, HD148816, lies outside Fig. 5 with  $[\text{Fe}/\text{H}] = -0.74$  and  $Z_{\text{max}} = 5.44$  kpc.), and Figure 6 plots  $[\text{Fe}/\text{H}]$  vs. orbital eccentricity. (We have not attempted to re-derive orbital parameters for the stars based on the new parallax results. Although there may be significant changes for a few stars, for the vast majority of these stars distances have changed only slightly and so the orbits will also change negligibly.) Two things can be discerned from these plots. First, there is a tight cloud of disk stars with mean orbital radii between 7.0 and 8.5 kpc, orbit eccentricities  $< 0.15$ , and  $[\text{Fe}/\text{H}] > -0.5$ . Second, most of the metal-poor stars in the sample have eccentric orbits that range far from the solar radius and away from the galactic plane. Edv93 also noted the increase in the vertical velocity dispersion for old, metal-poor stars in their sample (see their Fig. 16). It can be inferred from this that the sample is contaminated by thick disk stars and other stars from outside the solar circle.

The differences between the upper and lower panels of Figure 2 largely reflect the sample selection criteria used by Edv93. Metal-poor stars are more rare than metal-rich ones in the solar neighborhood. Thus, in order to have roughly equal stars in each metallicity bin, the metal-poor stars will be fainter and more distant, on average. Second, Edv93 selected stars which were at least 0.4 magnitudes above the main sequence but within the temperature range 5600-7000 K. Finding young stars that meet these criteria is more difficult than finding older stars. Therefore, the young stars will also tend to be more distant. The third difference is the fact that the stars in the outer shell with  $0.5 < \log \tau < 0.9$  are systematically more metal-poor than stars of the same ages in the inner shell. We suspect that this is also likely a result of the selection criteria, but this is more difficult to understand without modeling the selection biases. A comparison of the kinematics of the two sets could prove interesting, but is beyond the scope of this paper. Figure 2 makes it clear that this is not a randomly selected sample of stars. If the inner and outer circles

were fair samples of the solar neighborhood metallicity distribution, Figs. 2(a) and 2(b) should show similar age-metallicity relationships.

Finally, we compare the  $[\text{Fe}/\text{H}]$  distribution for the stars in the Edv93 sample with the volume-limited sample of G and K dwarfs from Favata, Micela, & Sciortino (1997). Favata et al. derived  $[\text{Fe}/\text{H}]$  for a random selection of 92 stars from the Gliese catalog of nearby stars. There are eight stars in common between Edv93 Favata et al.; the mean difference in  $[\text{Fe}/\text{H}]$  is  $0.03 \pm 0.03$  dex, suggesting no significant systematic difference in the two metallicity scales. However, Favata et al. noted a peculiarity in their  $[\text{Fe}/\text{H}]$  distribution, in that the cooler K dwarfs showed a higher mean and smaller dispersion in  $[\text{Fe}/\text{H}]$  than the G dwarfs. For fair comparison, therefore, we restrict our discussion to the 39 Favata et al. stars with  $T_{\text{eff}} > 5600$  K, the lower  $T_{\text{eff}}$  limit of the Edv93 sample, to be compared to the Edv93 stars within 30 pc of the Sun.

We plot the  $[\text{Fe}/\text{H}]$  distributions of these two samples as histograms in Figure 7. The Edv93 stars are clearly skewed toward lower metallicities compared to the Favata et al. sample, with the Edv93 sample missing the most metal-rich stars found by Favata et al., while showing an excess of stars in the range  $-0.1 > [\text{Fe}/\text{H}] > -0.4$ . Again, this could be a result of the metallicity selection in the Edv93 sample. It is probably not possible to say at present if the volume-limited sample has a smaller dispersion than the Edv93 sample, given the small numbers of stars involved. Unfortunately, the Favata et al. stars lack kinematic data, so a more detailed comparison is not possible at present.

#### 4. Discussion

It is apparent from this exercise that determining the shape and dispersion in the age-metallicity relation is not particularly straightforward, even for a high-quality data set such as the Edv93 sample. One must be careful to account for kinematically distinct populations, sample selection, and abundance peculiarities to derive a representative solar neighborhood sample. Although diffusion of stars from outside the solar circle does contribute somewhat to the scatter in abundances, it does not account for most of it, as was suggested by Wielen, Fuchs, & Dettbarn (1996). That this is the case can be inferred by comparing the Edv93 AMR with that from Twarog (1980). The measured dispersion in  $[\text{Fe}/\text{H}]$  at every age bin in the Twarog sample is smaller than that measured in the Edv93 sample; the dispersion in  $[\text{Fe}/\text{H}]$  in the Twarog sample ranges from 0.06 to at most 0.18 dex, compared with the 0.24 dex determined by Edv93. If stellar diffusion is responsible for most of the scatter in the Edv93 AMR, then the dispersion in the Twarog AMR should be at least as large as that of Edv93, not smaller. This reinforces the argument that the large scatter in the Edv93 AMR is most likely due to selection effects.

Twarog, Ashman, & Anthony-Twarog (1998) measured a dispersion in  $[\text{Fe}/\text{H}]$  of only 0.1 dex for galactic open clusters, which are presumedly less subject to diffusion effects than individual field stars. In comparison, the average dispersion in the Twarog (1980) AMR is 0.15 dex for field

stars with ages in the range 3-10 Gyr. If this represents the true dispersion in metallicity for the field stars, then the difference between the field star and cluster results (corresponding to a scatter of about 0.1 dex) could be attributable to stellar diffusion, although the effect of sampling from different parts of the galactic metallicity gradient needs to be accounted for as well. A comparison of the cluster data with a complete sample of field stars having kinematic data could provide a more stringent test of stellar diffusion.

Contamination by thick disk stars complicates the determination of the metallicities of the oldest thin disk stars. On the other hand, the kinematic data suggest that the thick disk may be an ancient population (see Fig. 31 of Edv93 and corresponding discussion in Freeman 1991). With larger complete samples of stars with metallicity and kinematic measurements it may be possible to subtract the thick disk contribution statistically. This would be a very important measurement because the initial metallicity of the thin disk is poorly known (as is its age as well). Determination of this quantity would provide an important constraint on chemical evolution models.

Abundance measurements for the interstellar medium in galaxies typically imply small dispersions in metallicity. Kennicutt & Garnett (1996) found a dispersion of only 0.1-0.2 dex about the radial gradient in O/H from 41 H II regions in the spiral galaxy M101, consistent with observational uncertainties and implying that the intrinsic abundance dispersion is negligible. Kobulnicky & Skillman (1996, 1997) found a dispersion in O/H of only  $\pm 0.05$  dex in the dwarf irregular galaxy NGC 1569, and  $\pm 0.10$  dex in NGC 4214. Closer to home, Meyer, Jura, & Cardelli (1998) have found a very small dispersion, only  $\pm 0.05$  dex in O/H, in local (within 500 pc) diffuse interstellar gas. The combined data from ISM and star cluster observations imply that the ISM is relatively well-mixed on size scales  $< 0.5$  kpc and  $> 1$  kpc, or that mixing occurs on sufficiently large spatial and time scales that supernova ejecta are considerably diluted by ambient gas.

Roy & Kunth (1995) and Elmegreen (1998) discuss mixing of SN ejecta on small ( $< 1$  kpc) scales. The implication from these studies is that it is difficult to maintain a metallicity dispersion greater than 0.15 dex because of the efficiency of mixing processes. Elmegreen (1998), considering the enrichment of clouds by supernovae, predicts inhomogeneities of only about 0.05 dex within molecular clouds. This level of inhomogeneity is indeed consistent with the abundance dispersion measured in interstellar gas, but not with the apparent dispersion on stellar metallicities. On the other hand, data on the dispersion in abundances on intermediate size scales is lacking. Further studies of interstellar abundances over size scales of  $\lesssim 1$  kpc, along with further studies of stellar abundances with age, are needed to improve our understanding of the distribution and mixing of heavy elements in our galaxy and others.

To summarize, we conclude that, while the Edv93 stellar abundance data provide invaluable information on the evolution of element abundance ratios over time, it is not possible to infer either the dispersion in metallicity nor even the shape of the age-metallicity relation from these data because of various selection biases, as pointed out by the authors themselves. As a result of

these biases, we infer that the intrinsic scatter in the Edv93 AMR must be much smaller than that measured. We therefore argue that the Twarog (1980) study remains at present the preferred determination of the solar neighborhood AMR, until a new study based on a complete sample of stars becomes available.

We thank B. Edvardsson, B. Gustafsson, A. Quillen, and R. Wyse for informative discussions, and V. Smith for comments on the manuscript. We also thank the referee, Bruce Twarog, for a very helpful and stimulating discussion of the issues underlying the analysis here. DRG is grateful for support from NASA-LTSARP grant NAG5-7734, while HAK acknowledges support from NASA and STScI through Hubble Fellowship HF-1094.01-97A.

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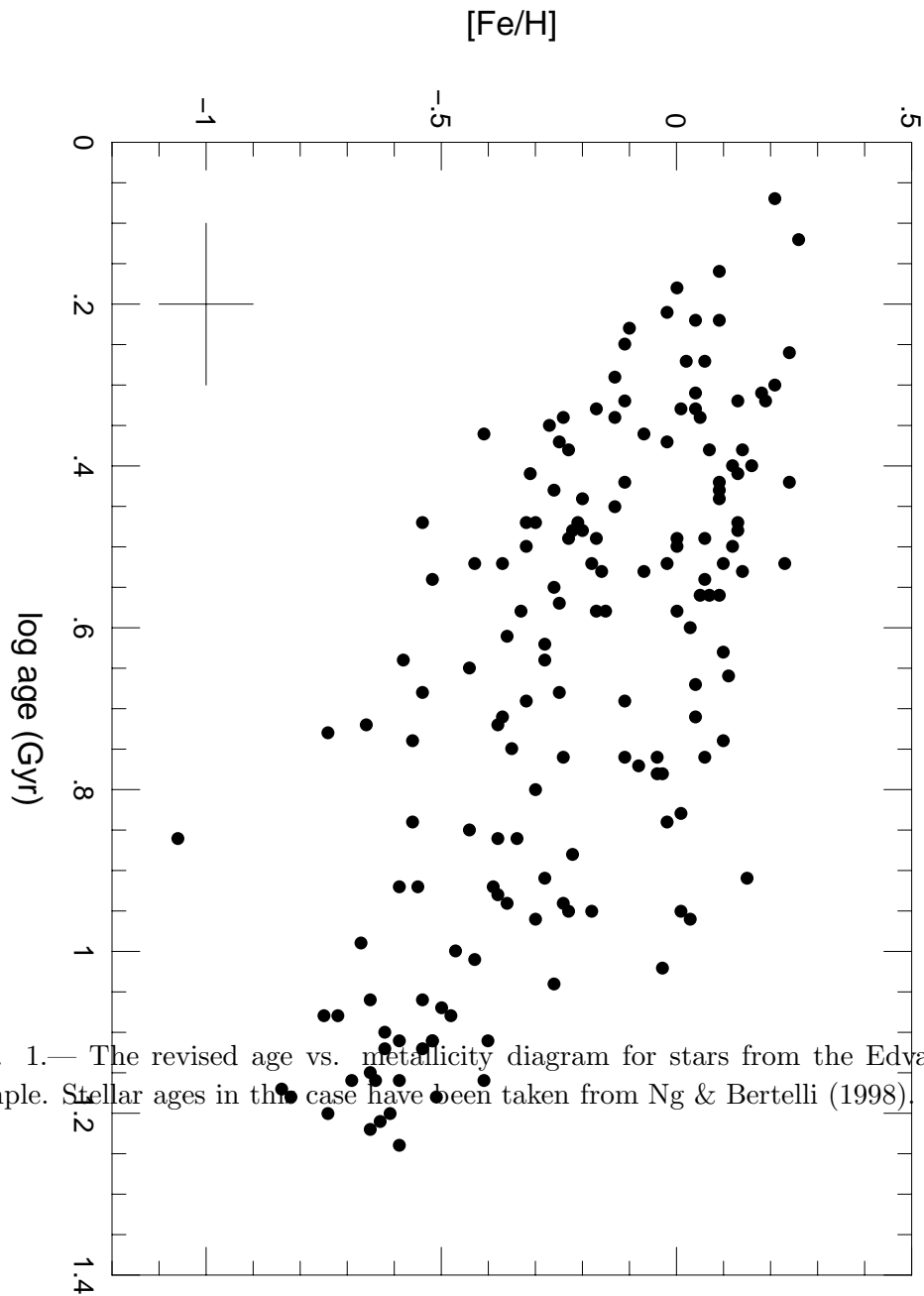


Fig. 1.— The revised age vs. metallicity diagram for stars from the Edvardsson et al. (1993) sample. Stellar ages in this case have been taken from Ng & Bertelli (1998).

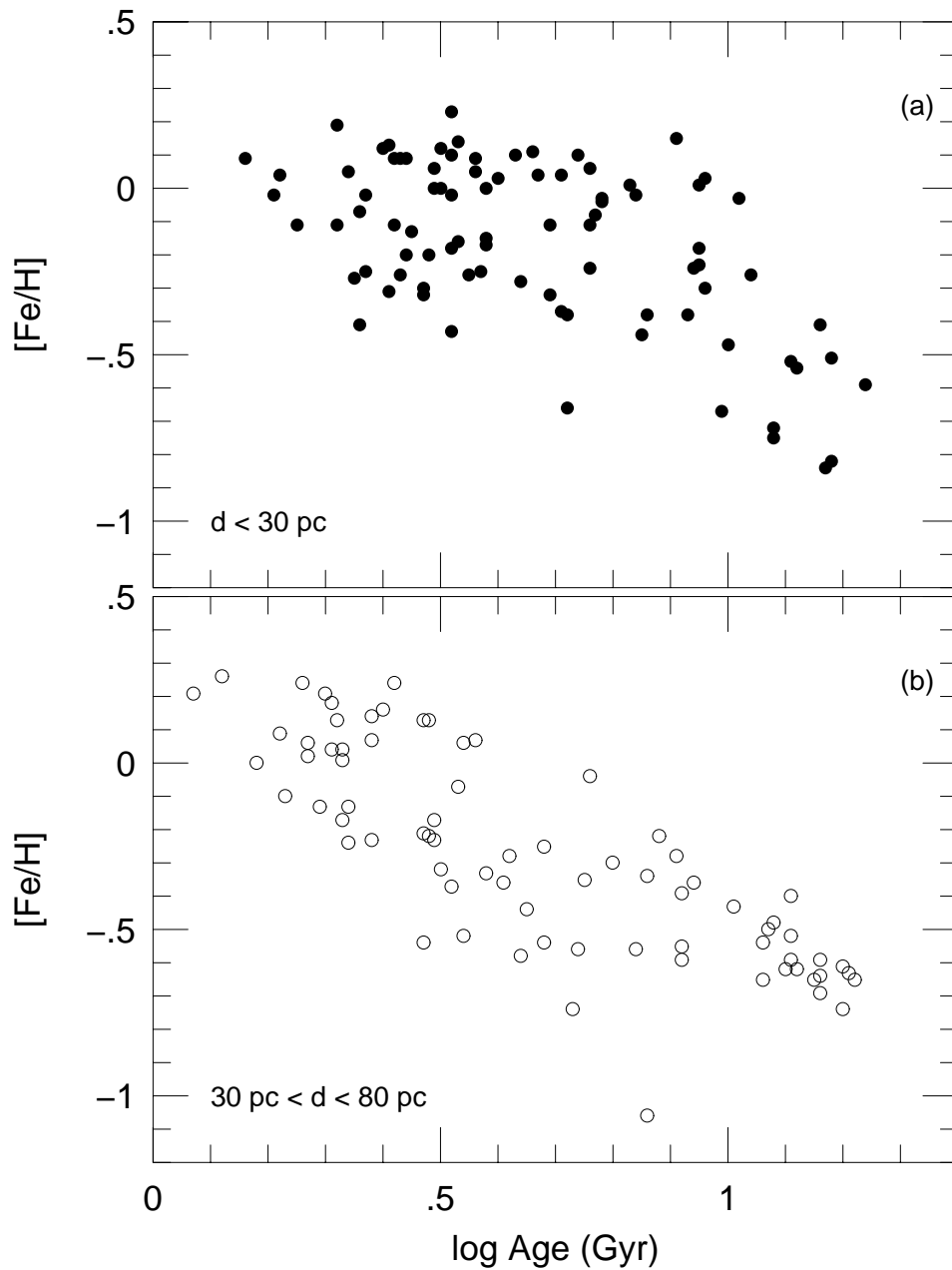


Fig. 2.— Age-metallicity relations for Edvardsson et al. stars, based on ages from Ng & Bertelli (1998) and distances from Hipparcos parallaxes. The sample is divided according to distance. (a) Stars within 30 pc of the Sun. (b) Stars between 30 and 80 pc distant. Note the strong asymmetry in the distribution of  $[Fe/H]$  between the two samples.

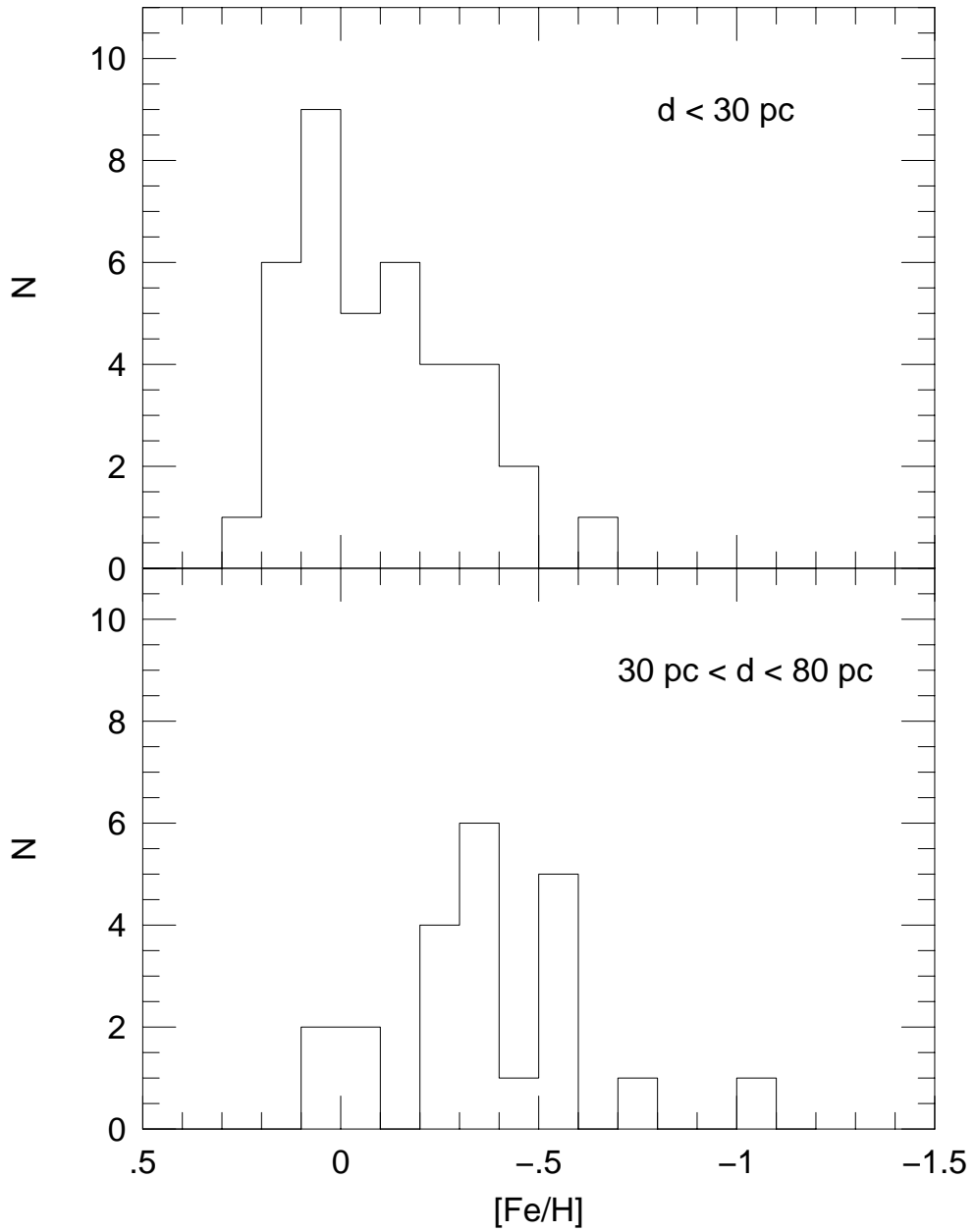


Fig. 3.— Histograms of the  $[\text{Fe}/\text{H}]$  distributions for stars in the age range  $0.5 < \log \tau(\text{Gyr}) < 0.9$ . The top panel shows stars within 30 pc of the sun; the lower panel shows the stars between 30 and 80 pc.

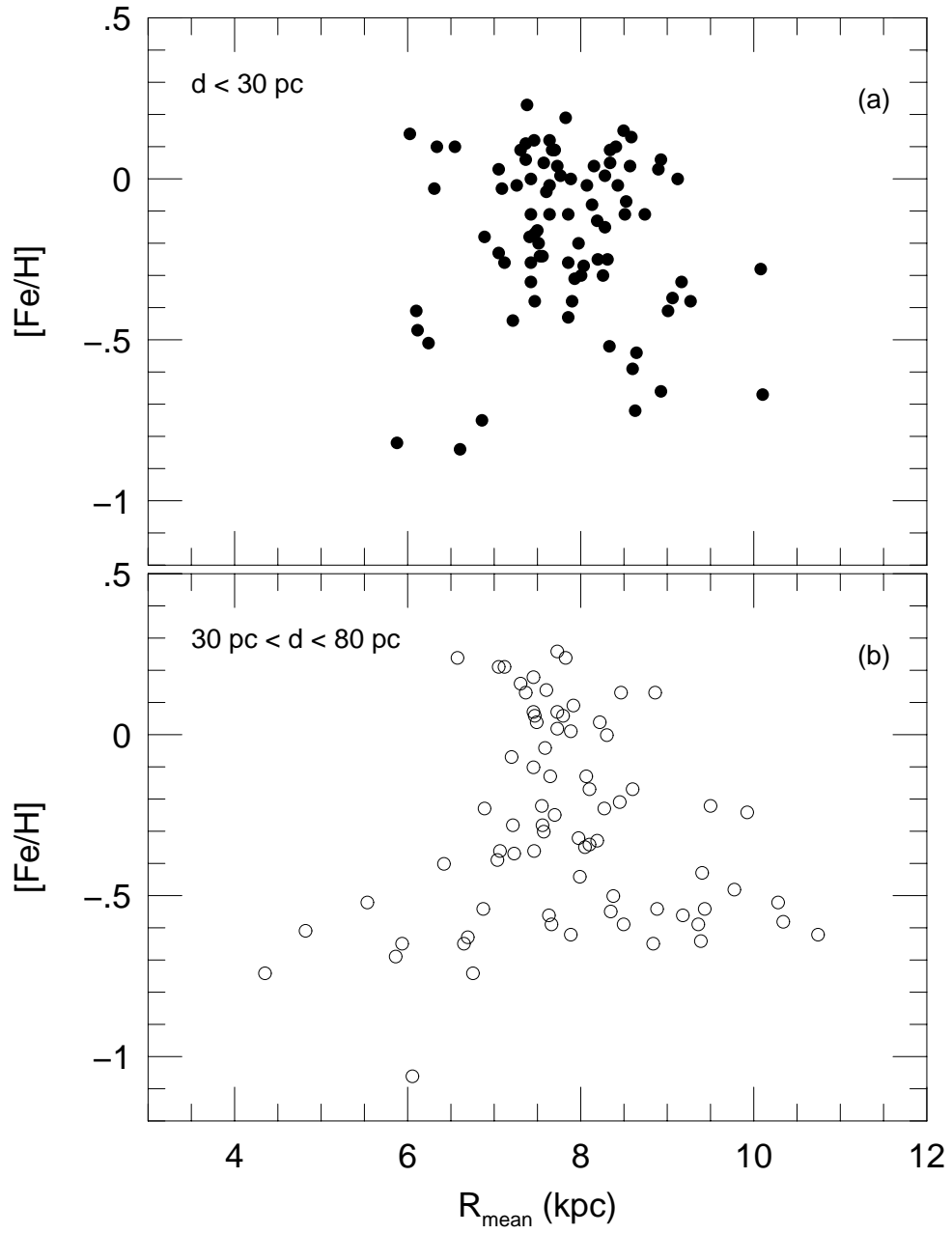


Fig. 4.— Stellar  $[\text{Fe}/\text{H}]$  plotted against mean orbital radius (taken from Edvardsson et al. 1993). Note that many of the metal-poor stars have orbits that range well beyond the solar circle.

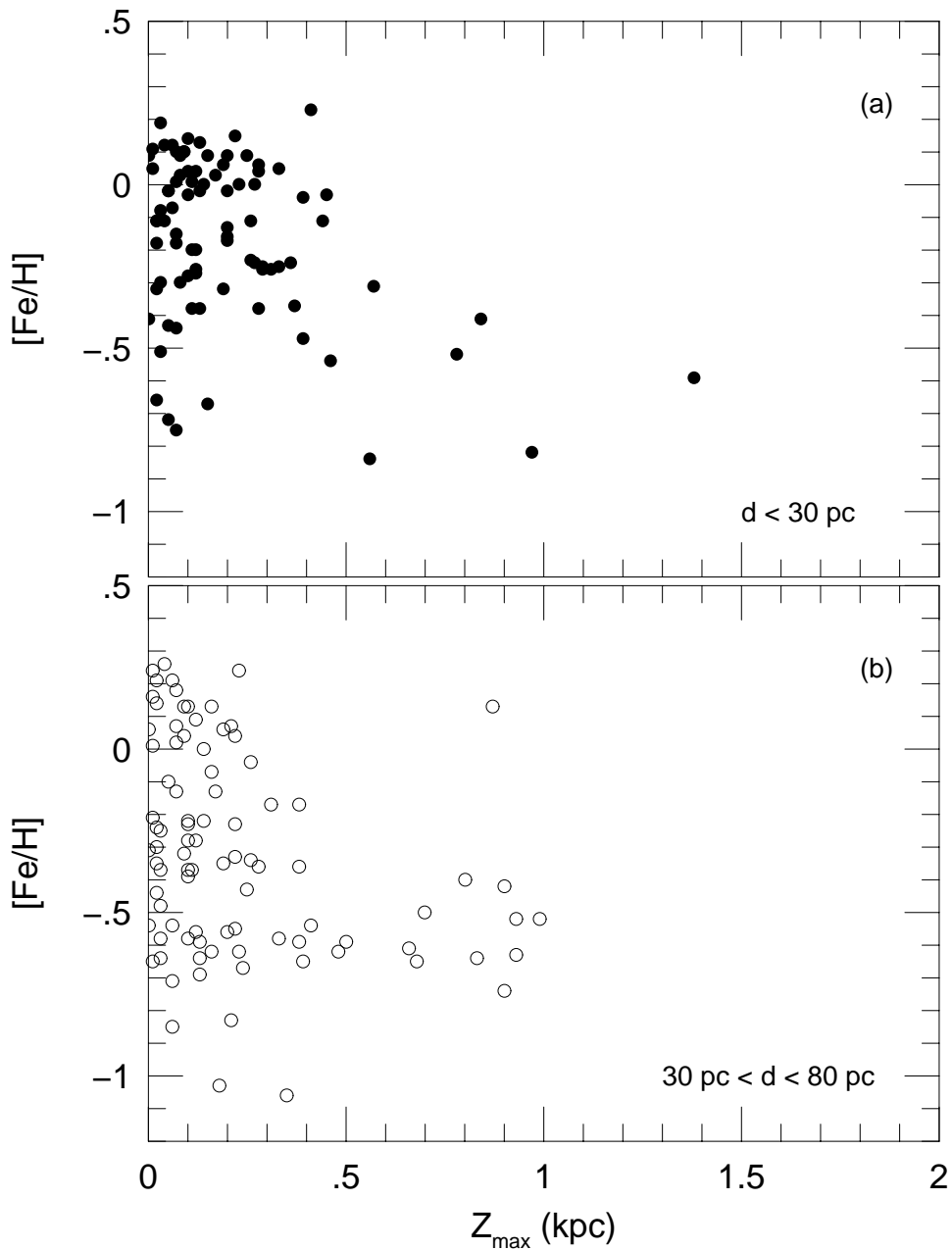


Fig. 5.— Stellar  $[\text{Fe}/\text{H}]$  plotted against maximum distance from the galactic plane (taken from Edvardsson et al. 1993). Many of the metal-poor stars range far away from the plane. One star, HD148816, lies off the plot at  $[\text{Fe}/\text{H}] = -0.74$ ,  $Z_{\text{max}} = 5.44 \text{ kpc}$ .

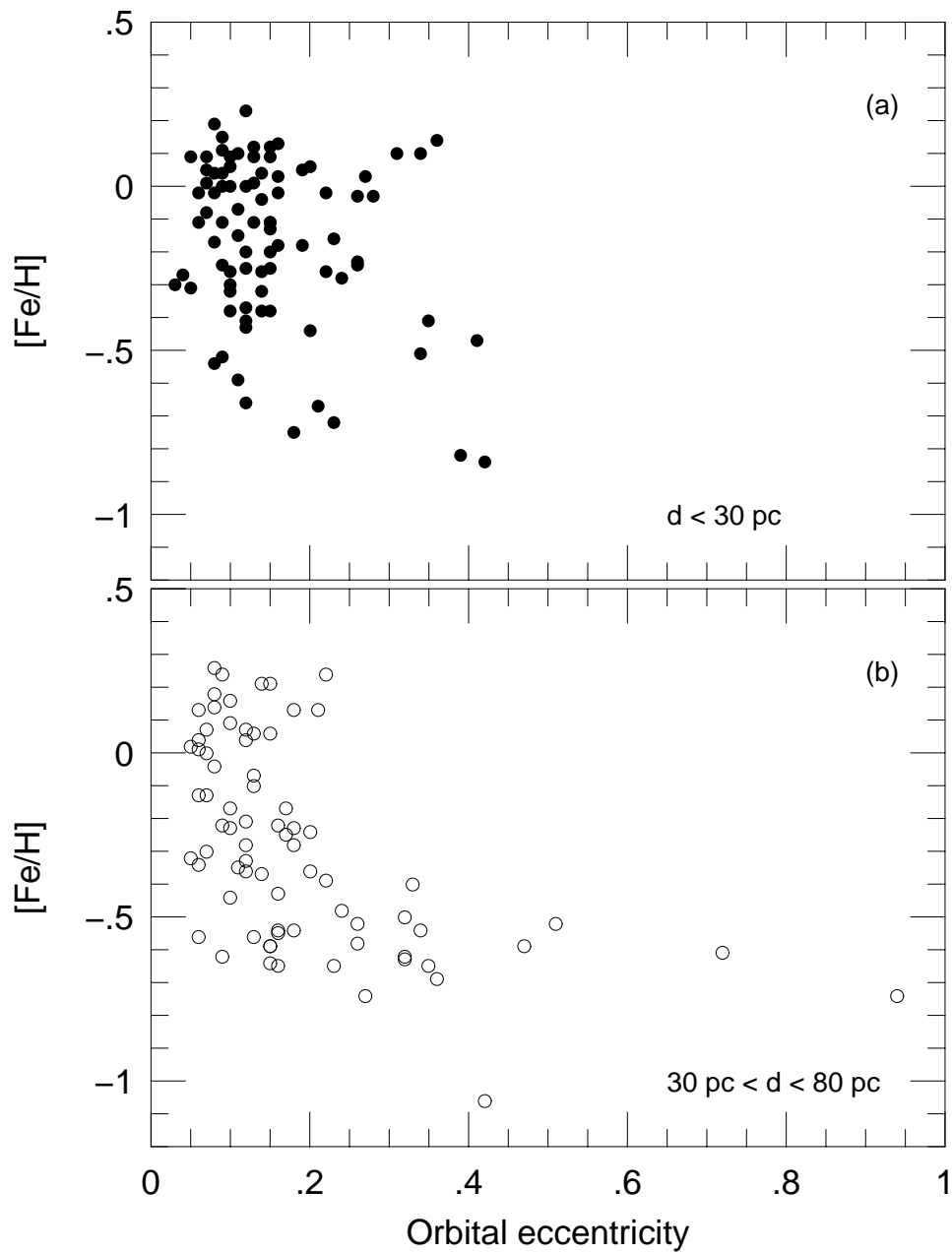


Fig. 6.— Stellar  $[\text{Fe}/\text{H}]$  plotted against orbital eccentricity  $e$  (taken from Edvardsson et al. 1993). Many of the metal-poor stars are seen to have highly eccentric orbits.

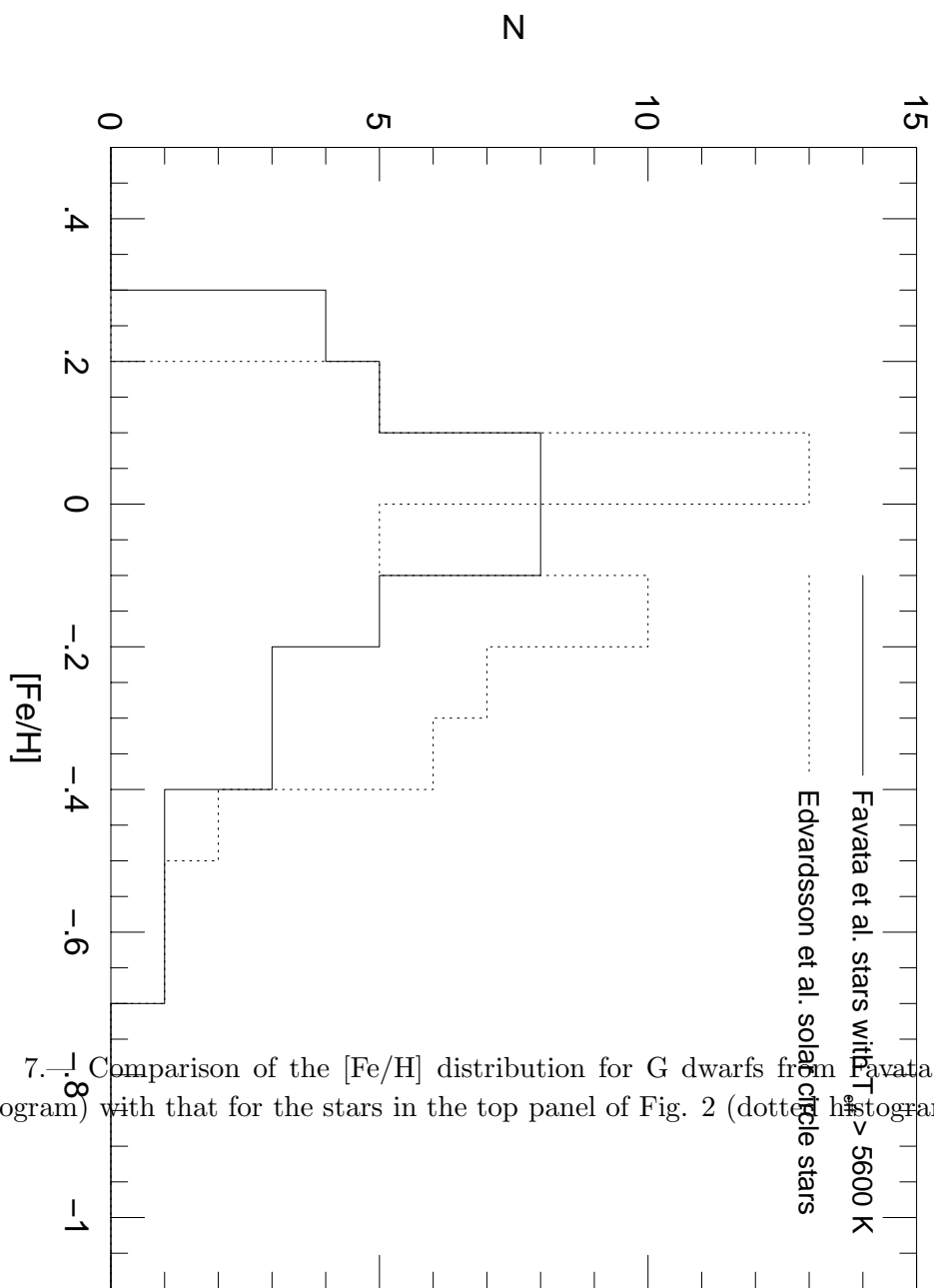


Fig. 7.— Comparison of the  $[Fe/H]$  distribution for G dwarfs from Favata et al. (1997) (solid histogram) with that for the stars in the top panel of Fig. 2 (dotted histogram).